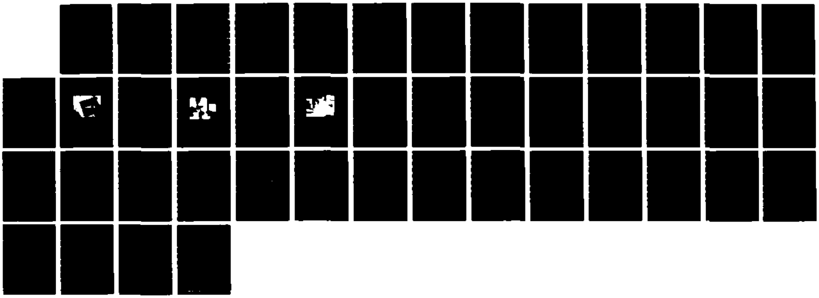
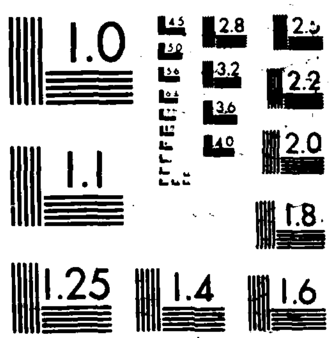
AD-A175 997 LABORATORY INVESTIGATION OF LIGHTWEIGHT HEATER TAPE FOR SHUTTLE PROPELLAN..(U) AEROSPACE CORP EL SEGUNDO CA AEROPHYSICS LAB D J SPENCER ET AL. 30 SEP 86 1/1

UNCLASSIFIED TR-0086(6930-01)-11 SD-TR-86-88 F/G 13/1 NL




1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

(12)

REPORT SD-TR-86-88

Laboratory Investigation of Lightweight Heater Tape for Shuttle Propellant Tank

D. J. SPENCER, J. F. BOTT, and J. S. WHITTIER
Aerophysics Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, CA 90245

30 September 1986

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, CA 90009-2960

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER SD-TR-86-88	2. GOVT ACCESSION NO. AD-A175 997
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) LABORATORY INVESTIGATION OF LIGHTWEIGHT HEATER TAPE FOR SHUTTLE PROPELLANT TANK	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER TR-0086(6930-01)-11
7. AUTHOR(s) Donald J. Spencer, Jerry F. Bott, and James S. Whittier	8. CONTRACT OR GRANT NUMBER(s) F04701-85-C-0086
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Los Angeles Air Force Station Los Angeles, Calif. 90009-2960	12. REPORT DATE 30 September 1986
	13. NUMBER OF PAGES 41
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Space Shuttle, Ice Formation Prevention, Ice Prevention, Heater Tape, VAFB Launch Site, Sprayed-on Foam Insulation (SOFI)

10-W/sq ft

approx.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experimental measurements under simulated typical operating conditions have established that the addition of surface (or near-surface) lightweight mylar electrical heater tape to external tank (ET) sprayed-on-foam-insulation (SOFI) panels results in an efficient approximately 67°F (36°C) surface temperature rise for a 10-W ft^{-2} applied power per unit area of SOFI surface. Consideration was given to the application of the lightweight mylar heater tape used in these measurements to the ice critical areas of

DD FORM 1473 (FACSIMILE)

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

the ET. A cryogenically cooled power distribution system capable of providing a 10-W ft^{-2} heating rate was investigated for a configuration covering 8545 ft^{-2} of ET area. Total onboard system weight was estimated to be approximately 33 lb with a total mylar heater tape weight of approximately 6 lb.

8545/sq ft

Keywords:

PREFACE

The authors wish to express their deep appreciation for the excellent assistance received from their coworkers in the performance of this study. The environmental chamber was constructed by H. A. Bixler and R. G. Aurandt with assistance from J. Valero. Tests were performed by P. R. Valenzuela and V. T. Hunt. Adaptation of the Cromemco microcomputer to the experiment was accomplished by M. L. Lundquist. Aluminized mylar was procured by W. A. Garber. Emissivity measurements were made by K. Herr and L. Cochran. Encouragement and Space Transportation System data were provided by H. A. Goedde and R. A. Hartunian.

CONTENTS

FIGURES

TABLES

I. INTRODUCTION

Ice accumulation represents a potential hazard to the orbiter on the Space Transportation System (STS) external tank (ET) surfaces. Of particular concern are the ogive nose regions (covering the LOX tank) and the upper reaches of the cylindrical regions (covering the LH_2 tank) that face the orbiter. Ice jarred loose from these regions during shuttle launch and ascent could damage orbiter Thermal Protection System (TPS) tiles upon impact. Present heat transfer and ice formation models predict that, in order to avoid ice-forming weather conditions, launches would be delayed more often at cold, foggy Vandenberg Air Force Base (VAFB) than at Kennedy Space Center (KSC).

Ice formation prevention on the surfaces of the sprayed-on-foam-insulation (SOFI) covered cryogenic propellant tanks of the STS external tank has been a matter of great interest for some time. Concern has increased as the imminence of launchings from VAFB grows. Numerous approaches to the deceptively simple problem of ice prevention have been advanced and studied. Uncertainties still attend the best proposed solutions. Twenty-three concepts have been considered and discussed in some depth.* The low efficiencies associated with the proposed forced convective or radiative heating schemes motivated our reexamination of direct energy addition of the SOFI surface.

One previous approach* involved application of electrically conductive paint to the SOFI material and surface temperature elevation by electrical heating. This method can assure no ice formation and was found to be an efficient method of heat application to the surface. However, several disadvantages to this method were noted: increased weight, increased paint/wire debris, and uneven heating resulting in a fire hazard because of local high temperature. In addition, conducting paint could only be applied to insulative surfaces. The recent availability of very thin uniformly

---

*"Martin Marietta Briefing Charts for Orbiter Ice Debris Protection Study," Phase I Technical Interchange Meeting, Vandenberg Air Force Base, Calif., 9 July 1981, pp. 230, 232.

aluminized mylar with properties that either reduced the significance of or nullified these disadvantages suggested that this material be investigated for a heater tape type application to a cooled SOFI surface.

The electrical heater tape concept is illustrated in Figs. 1 and 2. Figure 1 is a schematic cross-sectional view of a typical foam-insulated tank wall. SOFI is typically applied to the ET in two sequential 0.5-in. layers. The second layer is applied within ~10 sec to ensure bonding at the interface. Heater tape might conceivably be embedded at this interface through roll-on application of the tape just before spraying of the second SOFI layer. This was considered to be the closest possible placement site for the heater tape relative to the cryo tanks, since heat added too near the cryo surface only increases the cryogen boil-off rate. Alternatively, the heater tape might be embedded at a second interface between a second SOFI layer of say 0.375-in. thickness and a third SOFI veneer covering of about 0.125-in. thickness. This second placement possibility is illustrated in Fig. 1. A third placement alternative involves application of the heater tape to the exposed surface of the SOFI.

Conceptual steady-state temperature profile plots through the SOFI for conditions of 40°F (4.4°C) ambient air temperature and filled cryo tanks (T_{cyro} = −297.4°F (−183.0°C) for LOX, T_{cryo} = −422.9°F (−252.7°C) for LH_2 and both heater On and heater Off conditions are shown in Fig. 2 for a heater tape embedded just below the surface. The desirability of near-surface heat addition is apparent. Surface temperature could be maintained above freezing or possibly dew point temperatures.

In an earlier study,[1] an environmental chamber capable of independent atmospheric temperature and humidity control was constructed for use in studies of ice and frost formation on SOFI surfaces. We have adapted this apparatus to permit investigation of surface temperature control of LN_2-cooled

[1] J. F. Bott, D. H. Ross, D. J. Spencer, and J. S. Whittier, Laboratory Study of Space Shuttle Propellant Tank Icing, TR-0083(3464-02)-1, The Aerospace Corp. (17 May 1983).

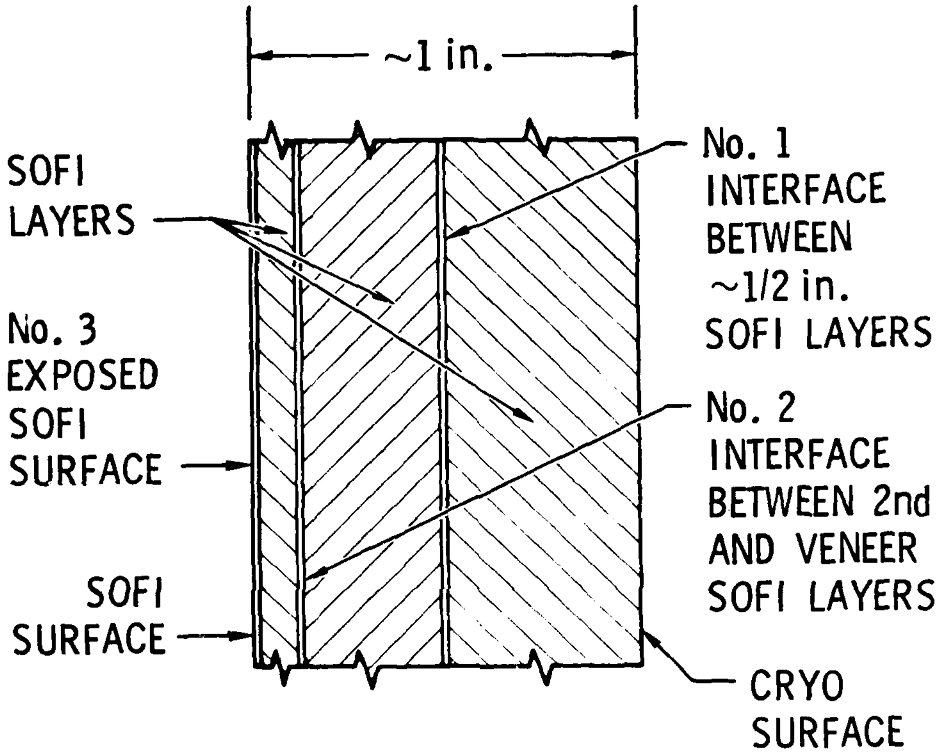


Figure 1. Heater Placement Options

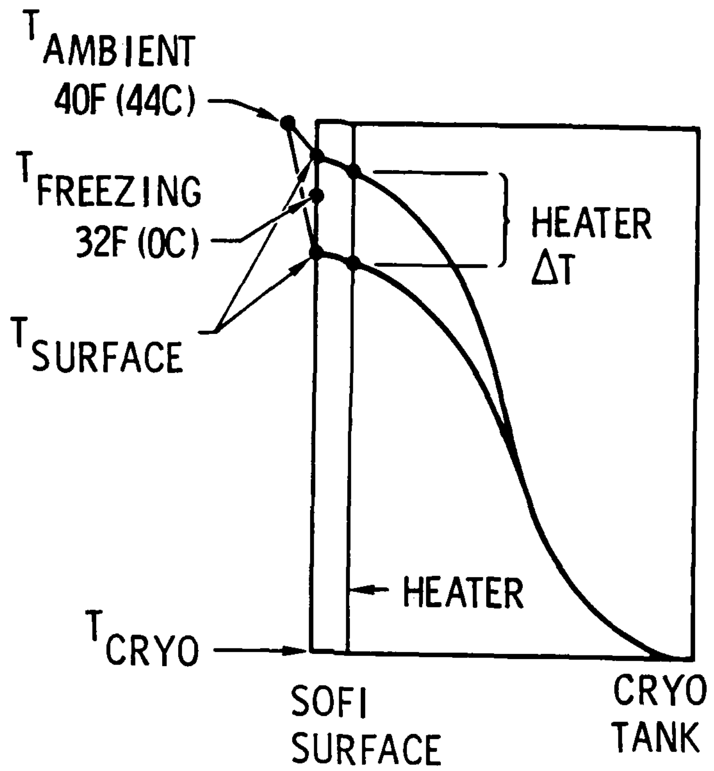


Figure 2. Conceptual Steady-State Temperature Profiles for Heater On and Off Conditions

SOFI panel surfaces by means of the lightweight electrical heater tape. Results of these heater experiments, together with the effects of electrical, mechanical, and weight considerations on full-scale application of the heater concept, are reported herein.

II. APPARATUS

The tests were conducted in an 8 × 8 × 12-ft insulated environmental chamber with a double panel window for visual observations. The chamber wall emissivity was approximately 1.0. Although the chamber had an air conditioner/blower in the ceiling, when the air conditioner was operated for several hours under high-humidity conditions, the coils frosted over, reducing the ability of the air conditioner to cool the chamber. Consequently, a large-area heat exchanger was placed in the chamber to permit cooling without excessive moisture extraction from the air. The heat exchanger was cooled with LN_2-chilled water-glycol mixtures to temperatures near freezing. The large heat exchanger was adequate to provide independent control of ambient temperature. The humidity in the chamber could be controlled independently with residential humidifiers to nearly 100% relative humidity (RH). In the current tests, humidity was of minor importance and was maintained at RH approximately 66.

Two cryogenic test panel fixtures were used in this test series to simulate a cryogen storage section of the external tank. A 24 × 24-in. test panel (No. 1) was used in preliminary tests and was fabricated with a low-density rigid polyurethane foam available in the laboratory, which was sprayed onto the test panel as a temporary substitute for the SOFI actually used on the external tank. The second test panel (No. 2) used for most of this study was 36 × 16-in. and was constructed with SOFI (CPR 488) covered front panel supplied by NASA/Martin Marietta.

The frameworks for the test panels were constructed from 1-in. square aluminum rods and conformed to the 24 × 24-in. and 36 × 16-in. panel dimensions. The frames were covered with 1/8-in.-thick aluminum sheets on both front and back. The aluminum sheets were fastened to the frame with machine screws and sealed with RTV silicone cement. The front aluminum sheets were covered with the SOFI to total thicknesses of 0.75 in. (24 × 24-in. panel) and 0.875 in. (36 × 16-in. panel). A 1-in.-thick sheet of styrofoam was used to insulate all other exposed aluminum surfaces on the cryogenic test panel fixtures to obtain low boil-off cryogen vessels.

The test panels were filled from a commercial LN_2 tank through a 1/2-in. insulated line leading to the test panel top edge. Nitrogen gas boil-off was exhausted through a second line to the outside of the building. The pressure in the test panels was monitored with a Heise Bourdon gauge, and the LN_2 flow rate was controlled to prevent a pressure buildup.

Thermocouples (Type T, Cu-Constantan) were attached with Scotch tape to the outside surfaces of the SOFI panels. The temperature profile through the thickness of the SOFI material was measured with thermocouples embedded at various depths. For placing thermocouples at various depths, a triangular trench with apex at the aluminum plate was cut through the rigid foam material. The thermocouples were pressed into the foam along the side walls of the trench and one was peened into the aluminum plate at the foam-aluminum interface. The thermocouple lead wires were routed for several inches along an approximately isothermal path to avoid temperature perturbations by heat conduction along the wires. After the lead wires were positioned, the triangular piece of foam was replaced in the trench and sealed along the edges with a thin application of RTV cement.

Test panel No. 1 was fabricated with two 0.375-in.-thick stacked layers of foam insulation. Half of the interface area between the two layers was covered with an array of aluminized mylar tape. Test panel No. 1 is shown in Fig. 3 during fabrication. The bottom foam layer is in position on the panel, and a strip of 2-in.-wide aluminized mylar heater tape is positioned in a parallel switchback pattern on one-half of the panel area. The aluminized mylar heater tape was held in position in the test fixtures by means of 3M Scotch tape or RTV silicone adhesive. In forming the right angle bends at the panel edge to reverse the heater tape direction, it was imperative that the aluminized surface of the mylar not come in contact with itself. Such contact would short circuit areas of the heater, radically change the sheet current flow, and concentrate the current over a small area resulting in a localized burn that would propagate across the entire tape width and cause an open circuit. The heater tape ends were coated with conductive adhesive and clamped at the ends in aluminum blocks to promote uniform sheet current flow through the heater.

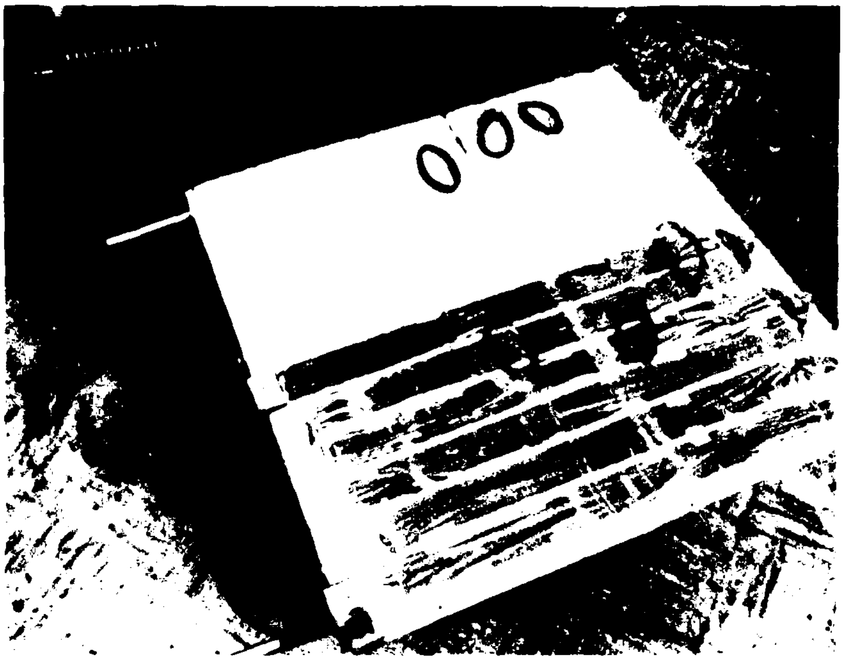


Figure 3. Test Panel No. During Fabrication with Aluminized Mylar Heater Tape Covering One-Half of the Panel

The bond line of the thermocouple trench and the coiled thermocouple lead wires is also shown in Fig. 3. The thermocouples were positioned one-fourth of the panel width in from the edges and thus were nominally in the center of each of the two distinct halves of the panel, one with the heater tape and the other without.

Further fabrication of this test panel involved spray-on addition of the top 0.375-in.-thick layer of foam insulation followed by thermocoupled installation from both sides in a triangular trench in the top layer. A heater tape was then applied to one-half of this surface over the area not containing an embedded heater below it. Finally, a 1/8-in.-thick sheet of styrofoam was spot-bonded over this area with RTV silicone adhesive. This finished test panel is shown in Fig. 4 being mounted and plumbed in position for test in the environmental chamber. Test panel No. 3 and the large area heat exchanger can also be seen in the background.

Panel No. 2 was fabricated with a front test panel obtained from Martin-Michoud. The 36 × 16 × 1/8-in.-thick aluminum sheet was sprayed in several layers to a total thickness of SOFI ranging from 1.50 to 1.75 in. This test panel was milled to 0.875-in. thickness, and thermocouples were placed in a trench cut across the 16-in. dimension near the panel center. Finally, the panel was sealed to the rest of the cryogenic test panel fixture.

The fixtures were tested while mounted vertically in the environmental chamber with their bottom edge approximately 6 in. from the floor. Thermocouple leads were directed to the outside of the environmental chamber where temperatures (in degrees centigrade) were logged at 1-min intervals with the aid of a laboratory microcomputer (Cromemco).

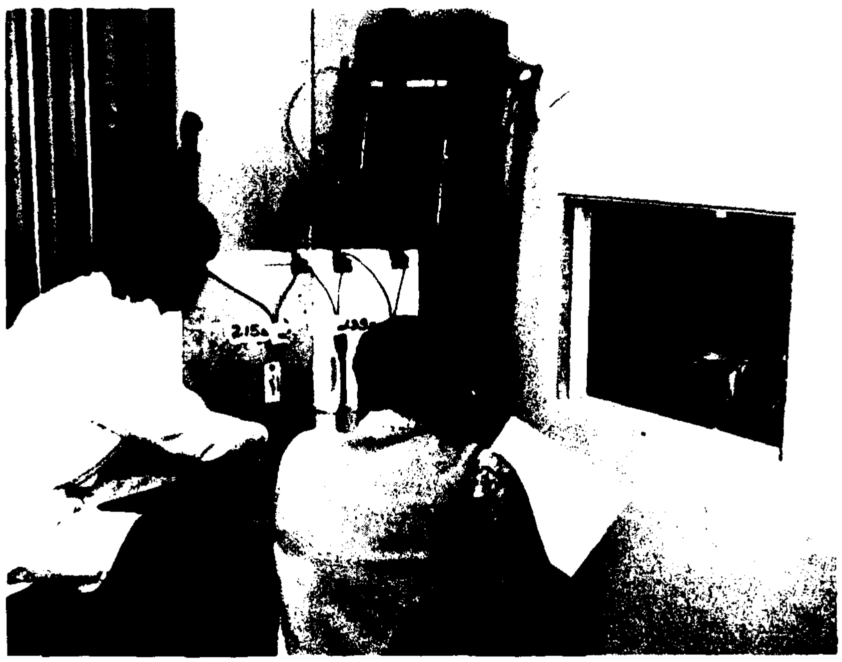


Figure 4. Test Panel No. 1 Being Installed in the Environmental Test Chamber

III. PROCEDURE

Cooling and filling of the cryogenic test panels required approximately 40 min. Thermocouple temperatures of the test fixtures and the experimental chamber atmosphere were monitored with a computerized recording system. During the cool-down period, the flow of LN_2 was carefully controlled to avoid any large pressure buildup in the panel that could have broken the seals. While the panel was being filled, the internal temperature of the environmental chamber was chilled to the desired ambient operating temperature by the built-in air conditioner and the large-area heat exchanger. The air conditioner was then shut off. During testing, the desired temperatures were maintained by making small adjustments to the LN_2 flow rates through the water-glycol bath of the heat exchanger. The thermal isolation of the environmental chamber was excellent and a long-term low ambient temperature was readily achieved.

Electrical power to the heater tape was monitored and variac controlled at a test control center outside of the environmental chamber near the observation window. The test control center, the environmental chamber observation window, and test panel No. 1 mounted in the chamber are shown in Fig. 5.

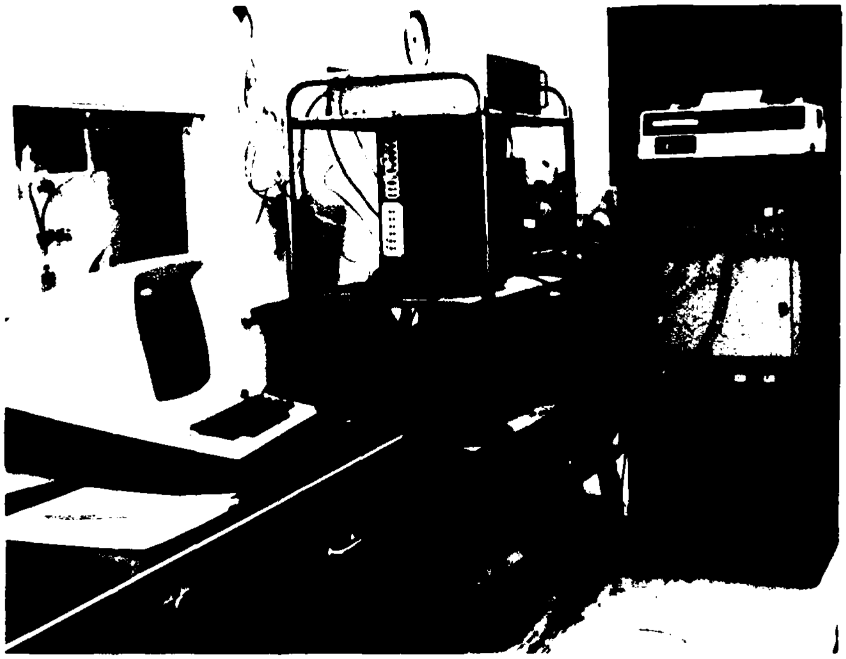


Figure 5. Test Control Center with LN_2-Cooled Test Panel No. 1 Seen Through the Observation Window

IV. RESULTS

A. TEST PANEL NO. 1

This test panel was constructed of readily available polyurethane foam for initial testing before acquisition of authentic SOFI sprayed panels in order to investigate heater and thermocouple mounting techniques and to gain some insight and direction for more formal testing.

The mylar strips were readily laid down and initially secured in place with 3M Scotch tape. (RTV silicone adhesive was later found to work very well and was used to secure the heater in position in test panel No. 2.) We had considerable difficulty in maintaining electrical continuity of the deeply embedded heater tape during the 40-min cryo filling period. Large cooling shrinkage of the mylar tape under conditions of constrained tape ends resulted in separation of the aluminum film across the width of the strip and hence an open circuit. This continuity problem was solved in the in-depth heater case by bunching the tape near the ends during installation to allow for cooling contraction. There was no difficulty with tapes located near the surface, where the temperature reduction was not so severe.

Steady-state temperature profiles are shown in Fig. 6 for heater On and Off conditions with the heater embedded midway through the polyurethane foam. The heating rate was 8 W ft^{-2}. The temperature increase at the embedded heater plane was substantial (ΔT = 54°F, 30°C), but this resulted in only a 5.4°F (3.0°C) temperature rise at the surface. This result clearly emphasizes the need to place the heater nearer the insulation surface. The S shape of the temperature profile is caused by the temperature dependence of the foam thermal conductivity.

Steady-state temperature profiles are shown in Fig. 7 for heater On and Off conditions with the heater embedded at the top layer foam and the 0.125-in.-thick styrofoam separation line. The heating rate was also 8 W ft^{-2} for this test. The large discontinuity in the temperature profile shown at the foam layer separation line is indicative of a condition of thermal

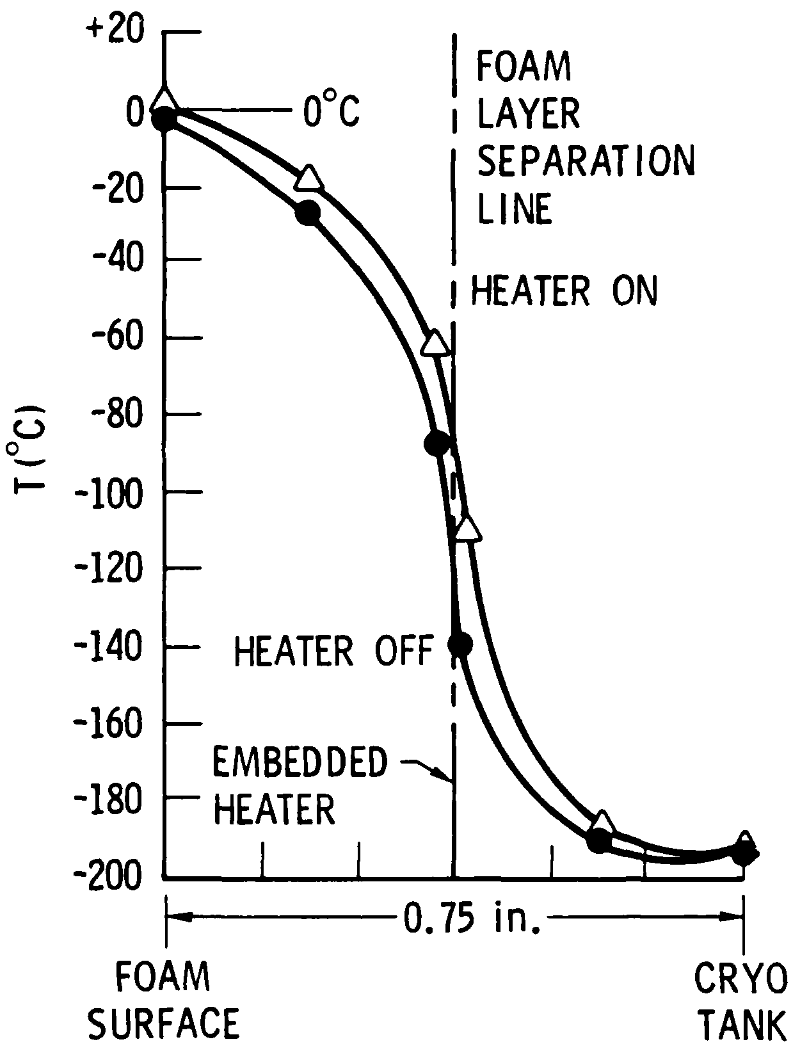


Figure 6. Steady-State Temperature Profiles with the Heater Embedded Between Foam Layers - Test Panel No. 1

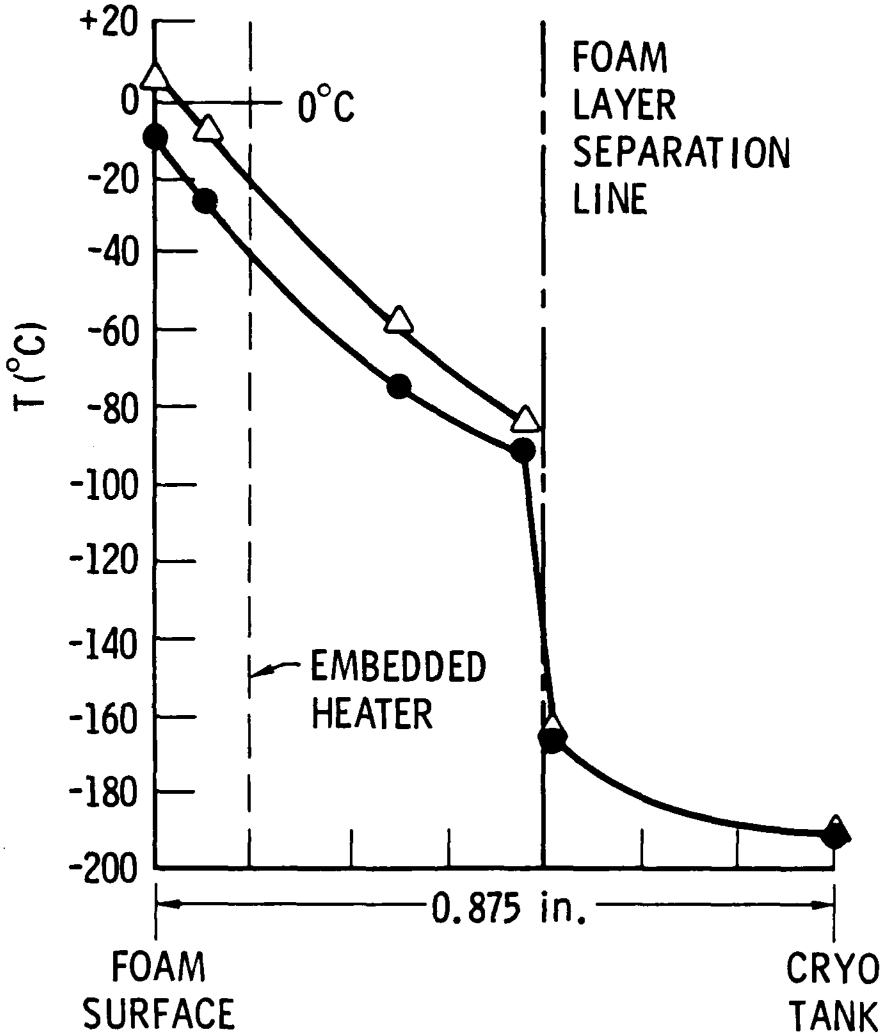


Figure 7. Steady-State Temperature Profiles with the Heater Embedded Near the Surface of the Foam Insulation - Test Panel No. 1

isolation of the two foam layers; it stands in strong contrast to the smooth profile of Fig. 6. Post-test examination revealed a gap of approximately 1.8 in. at this interface in the vicinity of the thermocouples. Thus, this test was somewhat compromised; comparison of the data of Figs. 6 and 7 does not give a straightforward picture of the effect of the change in heater position. Nevertheless, the qualitative features of interest, namely, greater influence on elevation of the surface temperature (ΔT = 28.8°F, 16.0°C) and reduced gradient near the cryo tank surface, are discernible.

B. TEST PANEL NO. 2

Steady-state temperature profiles are shown in Fig. 8 for heater On and Off conditions with a heater bonded at the interface between the 0.875-in. milled SOFI and a 0.125-in.-thick sheet styrofoam cover. The styrofoam sheet was held in contact with the SOFI surface by means of an open wooden "egg crate" framework. The ambient temperature was maintained initially at 47°F (8.3°C). The heater Off condition resulted in a steady-state surface temperature measurement of 25°F (-3.9°C). The styrofoam-SOFI interface temperature was 18°F (-7.8°C). The addition of 10 W ft^{-2} of heat at the interface resulted in a temperature increase of 36°F (20°C) to 61°F (16°C) at the surface and an increase of 54°F (30°C) to 72°F (22°C) at the interface.

The heater power influence on in-depth SOFI temperature was negligible at a distance half way through the SOFI. The smooth S-shaped temperature profile of Fig. 8 is indicative of a temperature dependence in the SOFI thermal conductivity.

The temperature rise at the heater tape interface and at the air surface is plotted in Fig. 9 as a function of heater power applied per unit area of SOFI surface. These data exhibit a linear dependence of temperature on power level over the range of 0 to approximately 10 W ft^{-2}. The shouldering in the curve that develops in the range of approximately 10 to approximately 30 W ft^{-2} results in a factor of 2 increase in temperature for a factor of 3 increase in heater power relative to the 10-W ft^{-2} value. This nonlinear feature of the thermal system is important. The application of a linear heating tape to certain contoured surfaces will require the presence of

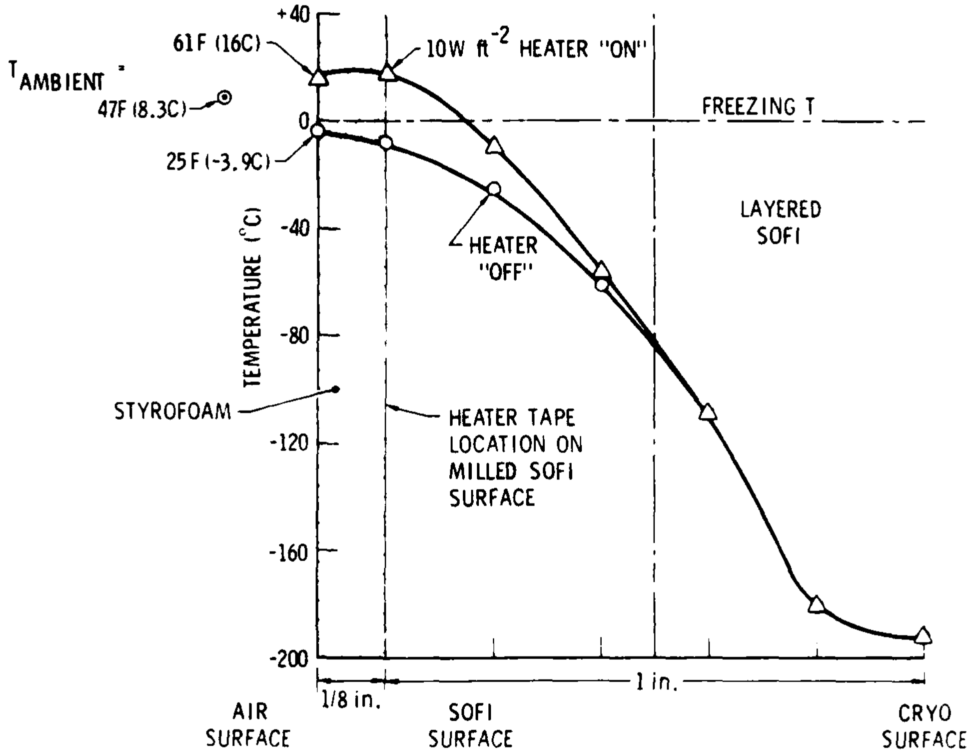


Figure 8. Steady-State Temperature Profiles with the Heater Near the Surface - Test Panel No. 2

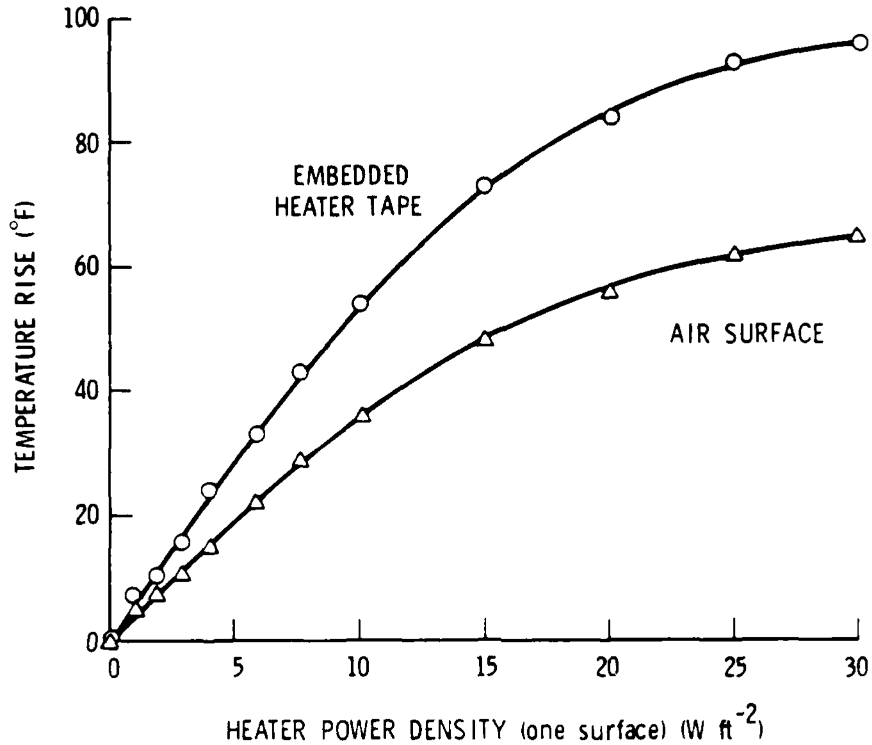


Figure 9. Temperature Rise vs Heater Power Density for Test Panel No. 2

overlap regions that will cause heater power to increase a nominal factor of 3 in the localized regions of the fold. Because of the nonlinear behavior, the local temperature rise in the fold areas will only be greater than the nonoverlap regions by a factor of less than 2. Thus, the application of the heater tape to surface contours requiring overlap will generate hot areas. These hot areas are controllable, however, in terms of the temperature rise in these areas relative to nonoverlap regions and, to a certain extent, their placement. They should not present a serious handicap to system implementation, since the hot areas can always be maintained at temperatures below SOFI damage threshold.

The temperature rise at the heater tape interface and at the air surface is plotted in Fig. 10 as a function of heating time. The temperature rise curve is exponential in form, as expected, with a $(1-e^{-1})$ time constant of about 3 min.

The curves of Fig. 8 indicate that the addition of heat just below the surface of a nominally 1-in.-thick slab of SOFI can raise surface temperature 36°F (20°C) above 25°F (-3.9°C), i.e.,approximately 29°F (16°C) above freezing for conditions of 10 W ft^{-2} power density and 47°F (8.3°C) ambient temperature. Iterations of test conditions about this test point were performed to verify performance expectations for conditions of ambient temperature change to 35°F (1.7°C) and to below freezing, 25°F (-3.9°C). The temperature profile curves for these tests are virtually identical to those of Fig. 8 except at the two outer interfaces of interest. In addition, similar tests were performed for the mylar heater tape applied directly to the SOFI surface with the aluminum surface ($\varepsilon \sim 0.1$) facing outward. The data points for the 47°F (8.3°C) ambient temperature case are plotted in Fig. 11. Results of temperature measurements are given in Table 1 for the two panel configurations, with and without styrofoam sheet covering, for the three ambient test temperatures, 47°F (8.3°C), 35°F (1.7°C), and 25°F (-3.9°C). In all cases tested, the surface temperature was below freezing for the heater Off condition and above freezing for the heater On condition. In general, a surface (or near surface) electrical power addition per unit surface area at the rate of 10 W ft^{-2} yielded approximately 67°F (~36°F) surface temperature increase over unheated

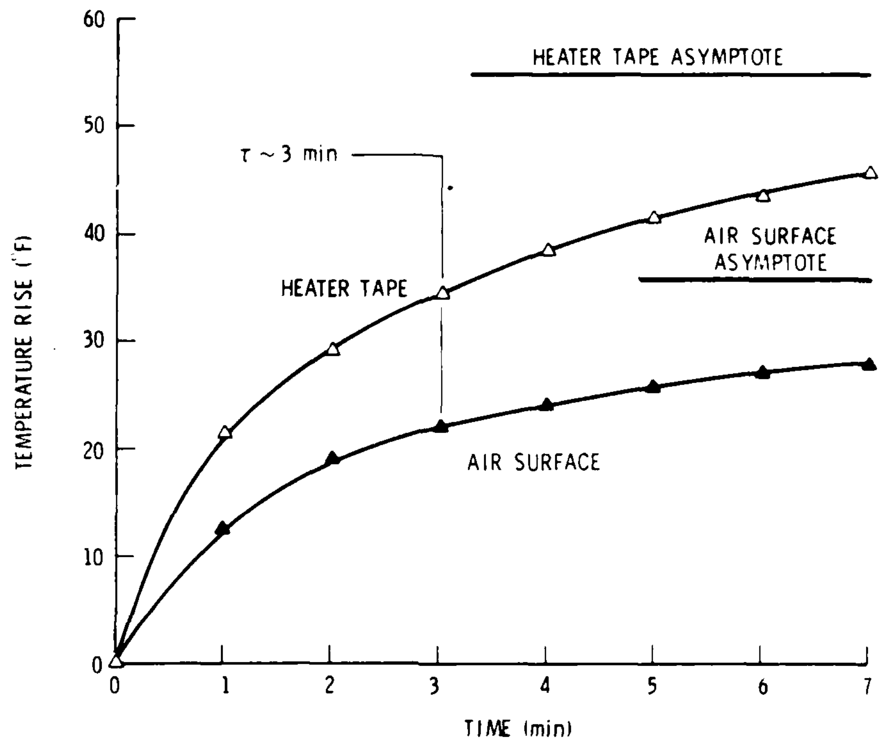


Figure 10. Temperature History After Heater Tape Turn On

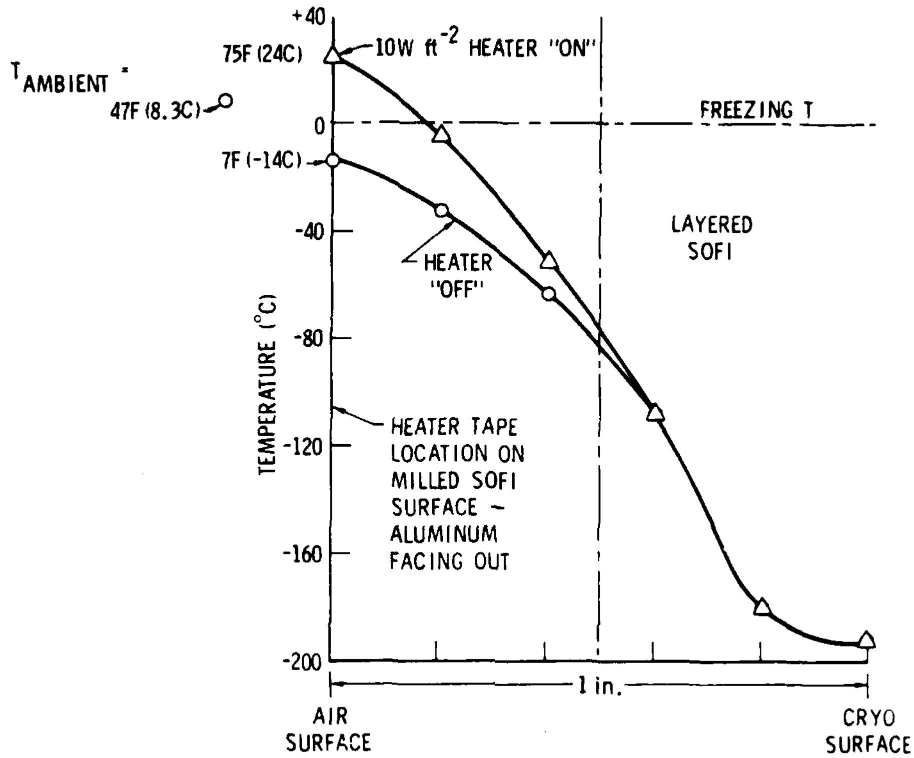


Figure 11. Steady-State Temperature Profiles for Heater On Surface - Test Panel No. 2

Table 1. Measured Surface and Interface Temperatures for Various Test Conditions

Ambient Temperature, °F(°C)	With Styrofoam Sheet: Interface Temp, °F(°C)			Without Styrofoam Sheet: Surface Temp, °F(°C) ($\varepsilon \sim 1$)			Without Styrofoam Sheet: Surface Temp, °F(°C) ($\varepsilon \sim 0.1$)		
	Heater Off	Heater On	ΔT	Heater Off	Heater On	ΔT	Heater Off	Heater On	ΔT
47 (8.3)	18 (-7.8)	72 (22)	54 (30)	25 (-3.9)	61 (16)	36 (20)	7 (-14)	75 (24)	68 (38)
35 (1.7)	8 (-13)	60 (16)	52 (29)	14 (-10)	50 (10)	36 (20)	-4 (-20)	63 (17)	67 (37)
25 (-3.9)	0 (-18)	52 (11)	52 (29)	4 (-16)	40 (4.4)	36 (20)	-13 (-25)	52 (11)	65 (36)

conditions for free convection conditions.

Heat transfer calculations based on the data of Table 1 indicate that about one-third of the heater tape thermal power flows to the cryogen reservoir and about two-thirds flows to the front air surface. About two-thirds of this power is radiated to the environment ($\varepsilon = 1.0$) for a SOFI type surface radiator ($\varepsilon \sim 1.0$), whereas only about one-tenth is radiated by the aluminum surface of the heater ($\varepsilon \sim 0.1$). The remainder is lost through free convection.

V. SYSTEM ASPECTS

A detailed investigation of all matters that pertain to implementing a heater tape thermal control system on the ET is beyond the scope of this experimental study. However, certain technical generalizations can be made relative to application of this film sheet heater type to the ET SOFI surface or near surface and to the electrical power requirements and the associated weight penalties such a system would require. The discussion that follows presumes the adequacy of a nominal 67°F surface temperature rise capability to generally ensure a no-ice or no-dew condensation surface condition.

A. HEATER TAPE APPLICATION TO SOFI SURFACES

The application of a mylar heater tape to a full-scale ET is a formidable task from several points of view. The first is simply the large scale involved. The areas of concern for ice control are indicated in Fig. 12 and have been calculated earlier* to be the following: the entire ogive nose region forward of STA 852 (2809 ft^2), the surface area ±100 deg of the +Z axis between STA 852 and STA 2058 (4838 ft^2), and a portion of the area aft of STA 2058 (898 ft^2) for a total of 8545 ft^2 that may require heating.

Bonding of the mylar tape to the SOFI surface requires the use of an adhesive. In this study, RTV silicone rubber cement and rubber adhesives were used for bonding on machined SOFI surfaces with excellent results even at cryogenic temperatures. Layup of the mylar tape on freshly sprayed SOFI while still warm and setting up is a possible production method that could produce bonding without the need of additional adhesive. However, it is expected that the SOFI spray-on operation may be sufficiently demanding that the additional complexity generated by specialized layup patterns required of the mylar heater tape in conforming with electrical distribution requirements and ET contours may preclude near simultaneous SOFI spray-on and heater tape layup.

*"Martin Marietta Briefing Charts for Orbiter Ice Debris Protection Study," Phase I Technical Interchange Meeting, Vandenberg Air Force Base, Calif., 9 July 1981, pp. 230, 232.

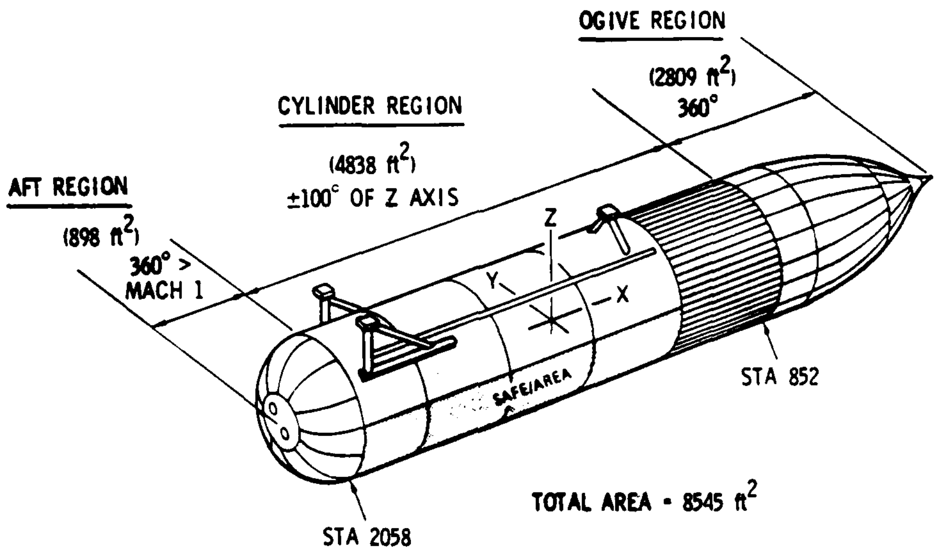


Figure 12. ET Ice Control Areas

Bonding of the mylar sheet to the SOFI surface results in a physical and associated temperature leveling of the outer contour to near the surface peak values. The local SOFI indentations become virtually sealed-off low-conductivity dead air spaces. Thus, large variations in neighboring SOFI surface temperature points due to uneveness (thickness specification = 1 ± 0.25-in. are significantly reduced. At a larger scale, the individual heater tapes should cover areas of similar SOFI thickness throughout the covered area in order to ensure a near-uniform surface temperature. About 10 lb of adhesive are required in order to provide a single bond to the SOFI.

If an outer SOFI surface is desirable, a final thin ($\lesssim$1/8-in.) SOFI overcoat might be applied directly to the primer coated aluminized film without the need for additional adhesive.

B. ELECTRICAL POWER HANDLING

It is recognized initially that the principle weight increment associated with a heater tape application to the ET resides in the electrical power distribution system. Consideration is given here to a sample onboard wiring harness distribution system with umbilical power disconnects located for convenience near ET STA 852 at the -100 deg line to illustrate the nature of the design considerations involved and to arrive at representative weight penalties.

The equations that govern heater tape performance in the application may be derived for the imposed 10-W ft^{-2} power flux constraint, i.e.,

$$P/A = 10 \text{ W ft}^{-2}. \tag{1}$$

The electrical power VI addition to the heater tape of width W and length L is therefore given by

$$VI = 10\ LW. \tag{2}$$

The application of Ohms' law

$$V = IR \tag{3}$$

and the relationship between resistance R and sheet resistance* Rs

$$R = Rs \frac{L}{W} \tag{4}$$

to Eq. (2) yields

$$V = L(10\ Rs)^{1/2} \tag{5}$$

and

$$I = W \frac{(10)^{1/2}}{(Rs)^{1/2}} \tag{6}$$

which relate the heater tape dimensions and sheet resistance to the external circuit voltage and current.

The desirability of minimizing the I^2R losses in the electrical distribution system drives one to maximize the voltage in the distribution system. the 2 μm mylar film has a minimum dielectric strength of 200 V. This film thickness and a maximum supply voltage of 200 V was selected for the illustrative sample design given here. In addition, the present maximum heater tape width for ultrathin mylar, 2 ft, was selected as a convenient-to-handle width size for application to the SOFI surface. The length of each tape for each of the three areas of concern is established for a convenient layup pattern by surface geometry considerations. Rs may then be determined with the aid of Eq. (5) for each value of L. Equation (6) may then be used to determine the current in each 2-ft-wide heater tape strip.

---

*Sheet resistance Rs is defined as the resistance of a uniform film of thickness t, length L, and width W, where L = W. Thus, Rs = ρ/t and is expressed in units of Ω/sq^{-1}. Multiplication of Rs by L/W yields the familiar Ohmic resistance R, since R = (L/W)Rs = Lρ/Wt = ρL/A, where A is the cross-sectional area.

The application of the heater tape to the central cylinder area between STA 852 and STA 2058 is the least complex geometrically and is discussed first. This surface area is nominally 48.4 × 100.0 ft. The area is covered with 50 2-ft-wide × 48.4-ft-long strips, oriented horizontally. Heater strip terminations lie along the ±100 deg lines that extend the length of the cylinder in this region of the ET. The calculated values for Rs and I for this layup are 1.71 Ω/sq^{-1} and 4.8 A, respectively. The total current flowing in this area is 240 A for a total power dissipation of 48 kW.

The heater strips are also deployed horizontally in the ogive nose region. The tapes extend completely around the circumference with the two end terminations lying side by side along a line, which, at its bottom is colinear with the -100 deg line on the ET cylinder and extends up along the ogive surface to the nose cone fairing. In this case, the strip lengths range from a maximum of 86.6 ft, the ET cylinder circumference, to approximately 22 ft near the nose cone fairing. The calculated values of Rs and I for the individual 2-ft-wide strips in this layup pattern range in intermediate discrete steps from 0.53 Ω/sq^{-1} to 8.3 Ω/sq^{-1} and 8.7 to 2.2 A, respectively. The total current flowing in this area is 140 A for a total power dissipation of 28 kW. The change in circumference with height requires overlapping of the individual heater tapes with respect to themselves in periodic triangular tucks to accommodate the flat tapes to this surface contour constraint. It is imperative that the exposed metallized surface be dielectric coated to ensure that no shorting of the conductor surfaces occurs in these regions of overlap. The temperature rise in these regions, as inferred from Fig. 9, will be nominally two times the temperature rise in the nonoverlap regions.

The aft region of the ET is handled in much the same way as the ogive region but with much greater overlap because of a more rapid evolution in surface contour. The total covered area is approximately one-third the ogive area, and the total current that flows in this region is approximately 45 A for a total power dissipation of only 9 kW.

These calculated values together with the required number of heater strips associated with this sample design are summarized in Table 2 for the

Table 2. ET Heater Tape Sample Design Values

Region	A, ft^2	P, kW	V, V	I, A	Rs, Ω/sq^{-1}	L, ft	W, ft	No. of Heater Strips
Ogive								
Top	44	0.44	200	2.2	8.3	22.0	2	
Bottom	173	1.73	200	8.7	0.53	86.6	2	
Total	2809	28.0	200	140.0		1404.5	2	19
Cylinder								
Top	96.8	0.97	200	4.8	1.71	48.4	2	
Bottom	96.8	0.97	200	4.8	1.71	48.4	2	
Total	4838.0	48.0	200	240.0		2419.0	2	50
Aft								
Top	173	1.73	200	8.7	0.53	86.6	2	
Bottom	44	0.44	200	2.2	8.3	22.0	2	
Total	898	9.0	200	45.0		449.0	2	8
Total	8545	85	200	425		4272.5	2	77

three considered areas. Note that the total power requirement of 85 kW is obtained from individual 200-V power systems of 425-A overall current capacity.

Power distribution to the 50 individual heater tapes in the central cylinder region is accomplished through the use of 100 individual distribution wires, 50 located along each of the two vertical lines at ±100 deg formed by the terminations. The wires to one side of the array lead from the power junction station near the top of the -100 deg heater strip array line directly down to each heater strip. Wires to the other side of the array are first routed from the junction station around the circumference of the ET. The last 2 ft of each wire are uninsulated and bonded uniformly to the aluminum strip by means of a suitable conductive adhesive.* The total wire length required for this array is 2550 ft (near side vertical, i.e., = 2 + 4 + 6 +...+ 100) + 2550 ft (far side vertical) + 2400 ft (50 horizontal wires to far side along 48-ft distance along circumference) + 100 ft (100 wires 1-ft long to junction box) = 7600 ft.

The wire was sized such that the 4.8 A flowing through each distribution wire would generate approximately 10 W ft^{-2} of wire surface area and is considered reasonable as a local additive heat load. This wire size selection criterion determines a No. 16 aluminum wire as adequate for water freezing temperature operation. However, extending the distribution wire along the LH_2 tank in intimate thermal contact with it under the SOFI insulative layer could result in a current conducting wire temperature reduction to about -200°C [T_{cryo} (LH_2) = -252.7°C], which in turn could cause a resistivity reduction in aluminum to about 0.2 the water freezing temperature value. Hence, a near-cryogenic temperature power distribution system may be constructed with No. 20

*The following conductive adhesives have been successfully tested to uniformly bond wires to aluminized mylar: Silver Print, an air drying silver conductive paint for printed circuits, manufactured by G. C. Electronics, Rockford, Illinois; DEVCON F, an 80% aluminum putty that requires the addition of a hardening agent as with an epoxy (hardening occurs in 1-1/2 to 2 hr at 70° to 75°F), and DEVCON aluminum repair, a single component conductive adhesive, both manufactured by DEVCON Corp., Danvers, Massachusetts.

aluminum wire. The 200-V operational level allows the use of low-voltage insluation. The No. 20 bare aluminum wire weighs 0.939 lb/100 ft. Thus, total wire weight for this cylinder section distribution system is approximately 7.1 lb.

One may similarly estimate the aft end power distribution wiring requirements. The circumferential heating tape strips terminate at each end along the line extending into the LH_2 bottom section that is the extension of the near side heater tape termination line at -100 deg. Eight heater tape strips are estimated to be adequate for covering this region. The total wire length required for this section is 144 ft (wire lengths from cylinder base to 8 heater strips and return) + 1600 ft (16 vertical wires 100 ft long along cylinder length) + 16 ft (16 wires 1 ft long to junction box) = 1760 ft. Variable wire sizes may be used for power distribution in this region, since currents range from 2.2 to 8.7 A in the individual heater strips. However, cryogenically cooled No. 18 wire with 4.8-A capacity is assumed here to adequately approximate the average wire size for sample calculation purposes. The total No. 18 wire weight for this distribution system is approximately 1.2 lb.

The total power distribution wiring requirement is thus estimated to be 7.1 + 1.6 + 1.2 ≈ 10 lb. Total power dissipation in the power distribution system is approximately 1% of the power dissipated in the heater tapes. Low-voltage insulation for the wires is estimated to be about 5% of the wire weight, or approximately 0.5 lb. The conductive adhesive requirement for wire-to-aluminum bonding weighs about 0.1 lb. Adhesive for bonding the mylar tape to the SOFI surface weighs about 10 lb. Cable clamps, junction box, and other system mounting items weigh about lb. The total aluminized mylar weight is also about 6 lb, which includes weight addition for some heavy gauge (6- μm thickness) usage as low Rs heater tapes on the ogive and aft sections.

The weight requirements for implementation of the onboard heater tape system are summarized in Table 3. The total system weight is $\lesssim$33 lb.

Wiring harness installation would involve cutting trenches of suitable size (~2-in. wide) in the SOFI along the heater tape termination lines and

Table 3. Weight Estimate Summary for ET Onboard Heater Tape System

System Component	Weight, lb
Aluminized mylar	6.0
Distribution wire	10.0
Wire insulation	0.5
Conducting adhesive	0.1
Mylar adhesive	10.0
Mounting hardware	6.0
Total	32.6

deploying the wires in side-by-side array (~30/in.) on or near the metal tank surface. Conductive adhesive bonding of the heater tapes to the individual wires would also be made in this trench. The cutout sections could thereafter be rebonded in place or alternately the trench would be resprayed with SOFI.

Preservation of the electrically isolated individual heater tape wiring scheme throughout the harness to the junction box allows individual external control of the 77 heater tapes. Thus, strip-to-strip variations in SOFI thickness may be readily compensated for electrically to achieve near-uniform surface temperature. Individual ogive and aft portion strips with overlap areas may also be individually calibrated for operation within minimum and maximum temperature limits. It is expected that external circuits sensitive to system-calibrated values for Rs would be set for $\tilde{>}33^\circ$F turn-on and stabilization to preclude ice information and minimize power usage and cryogenic fluid boil-off. The heater system could also be set to hold the surface above the dewpoint if this were desirable to ensure against water condensation on the SOFI surfaces.

V. CONCLUSIONS

Experimental measurements under simulated typical operating conditions have established that the addition of surface (or near-surface) heater tape to ET SOFI results in an efficient approximately 67°F (~36°C) surface temperature rise for a 10-W ft^{-2} electrical power flux. Consideration was given to the application of the lightweight mylar heater tape used in these measurements to the ice critical areas of the ET. A cryogenically cooled power distribution system capable of providing a 10-W ft^{-2} heating rate was investigated for a sample horizontal heater tape layup configuration. The total onboard system weight to implement this system was estimated to be approximately 33 lb.

A previously considered direct energy addition method involved the application of electrically conductive paint to the SOFI surface and temperature elevation by electrical means. A comparison of this method with the mylar heater tape method of this study shows that the positive features (i.e., no ice formation on the acreage and energy efficiency of the heat application methods) are both retained in the mylar heater tape method. In addition, the undesirable or limiting features of the conductive paint method, which precluded further development of this technology, are rectified by this new technology.

In Table 4, these features are compared and the superiority of the mylar heating tape method is illustrated. The positive features of this lightweight heater tape system suggest that consideration might well be given to further study and implementation of this heating method as a primary ET ice prevention method on critical areas if not the entire acreage area.

Table 4. Comparison of Conductive Paint and Mylar Heater Tape Characteristics as Applied to ET Surface Heating

Characteristic	Conductive Paint[a]	Mylar Heater Tape
Ice formation	None	None
Power efficiency	Efficient	Efficient
Weight (heater)	900 lb	~6 lb
Weight (total)	Not estimated	~33 lb
Debris	Wire and paint	<0.2 lb aluminum
Evenness of heating	Uneven - uncontrollable hot spots resulting in possibility of SOFI ignition	Even - controlled hot areas with a factor of 2 temperature increase on the surface at folds
Surface constraints	Insulative surfaces only	None
Temperature control	Unknown or difficult	Controllable at individual heater tape level

[a]"Martin Marietta Briefing Charts for Orbiter Ice Debris Protection Study," Phase I Technical Interchange Meeting, Vandenberg Air Force Base, Calif., 9 July 1981, pp. 230, 232.

APPENDIX

ALUMINIZED MYLAR HEATER TAPE

The aluminized mylar film used in this experimental study was obtained from an Electrocube 100 μfd double-layer film capacitor. The single-layer film was calculated to be 1.7 μm in thickness based on a weight measurement and an assumed average density of 1.395 g cm^{-3}. The thin mylar, a recent development of DuPont, is called Ultra Thin Type C Mylar Polyester film. It is available in thicknesses of 1.5 μm (±17%) (type 6C) and 2.0 μm (±13%) (type 8C) in rolls from 3/8 in. to 24 in. in width and lengths to 440,000 in.*

Uniform evaporative aluminization of the mylar film is performed by Steiner Film Inc. of Williamstown, Massachusetts. The aluminum coating is uniform in thickness along the width within a few percent. The uniformity with length is about ±5% for heavy coatings (>500 Å) and reduces to about ±20% for the more difficult to control thin coatings (~100 Å). Deposition rate is feedback-controlled by real time direct measurement of the sheet resistance of the film.

The addition of heat to the thin mylar films during evaporation limits the allowable aluminization thicknesses. Thicknesses of $\gtrsim$100 Å require the use of heavier films (say 6 μm). The aluminized mylar sheet resistance Rs versus evaporated aluminum thickness t relationship over the thickness range of 100 Å $\lesssim t \lesssim$ 1400 Å is given approximately by

$$Rs = \frac{600}{t(\text{Å})} \qquad \text{(A-1)}$$

The achievement of high-impedance films, $R_s \gtrsim 8\ \Omega/sq^{-1}$ with greater uniformity may be accomplished by adding zinc to the aluminum. Sheet resistance is always greater than the corresponding bulk sheet resistivity for

*Mylar data obtained from Mylar C Ultra Thin specification sheet, courtesy of DuPont Co.

the same thickness as a result of the amorphous nature of the evaporatively deposited aluminum layer with its attendant large lattice irregularity.*

The minimum tensile strength of the film is 10,000 psi, which translates into approximately 1.2 lb for a 2-in. wide strip. Breakage strength for a 2-in. strip was empirically determined to be about 5 lb. The film is tough and not easily punctured with moderately sharp instruments of ball point pen sharpness.

Aluminization of the 2.0- μm mylar film with 100 Å (1000 Å) aluminum adds only about 1% (~10%) to the film weight. A 250- Å aluminized single-layer film of area sufficient to cover the entire 8545 ft^2 desired no-ice area of the ET would weight approximately 5.09 lb, of which 4.97 lb is mylar and 0.12 lb is aluminum.

*Aluminized mylar data obtained from Steiner Film Inc., Williamstown, Massachusetts.

END

2-87

DTIC